CHAPTER 5

APPLICATIONS OF NANOMATERIALS

LEARNING OBJECTIVES

- Introduction, Photonic devices, Light emitting diode (LED)
- Solar cell, Single electron devices, Carbon nanotube.
- CNT based transistors.

5.0 INTRODUCTION

Nano-materials are the materials that are processed in the nanoscale. Nano-materials are different from other materials because nano-materials have a massive surface area. Nanoparticles are extremely reactive compared to their larger form because nano-materials have very high surface area. This property of nanoparticles, is used to create materials with distincitve characteristics for various applications. Carbon nanotube (CNT) is a nano-material application. Carbon nanotubes have a very high strength due to the higher surface area of its originating materials. In the nano-level quantum effects have a higher effect on the behaviour of particles. Hence some materials have special effects that have been utilized smartly to produce innovative products. The magnetic, electrical and optical properties can be effectively exploited to certain applications. For an example if gold particle can be reduced to 2nm radius then their melting point can be lowered remarkably.

Basically the applications of nano-materials can be divided into several categories. Thin films and engineered surfaced fall in to the one dimensional applications of nano-materials. These materials are used in the field of electronics and chemistry and they cannot be considered as new materials. Nanotubes and nanowires fall in to the two dimensional applications of nano-materials. Nanowires are ultrafine wires or linear arrays of dots that are formed self-assembly. Semiconductor nanowires are proudced by silicon. Nanodots and nano-particles like dendrimers and fullermes fall into the three dimensional applications of nano-materials. Dendrimers are spherical polymeric molecules that are formed through a nanoscale self-assembly process.

5.1 PHOTONIC DEVICES

Photonic devices are the electronic devices for creating, manipulating or detecting light.

Photonic devices are less sensitive to interference. Light emitting diode (LED), photo diode, laser diode and solar cells are examples of photonic devices. These devices can be fabricated using quantum dots, nanowires and thin films.

5.2 LIGHT EMITTING DIODE (LED)

Light emitting diode (LED) emits light spontaneously and it is constructed through a semiconductor PN-junction. It is an important class of optoelectronic device which is available over a wide range of colours. If the PN-junction is forward biased then it emits visible light in the form of photons. The energy of each emitted photon is nearly equal to the band gap of the system. Depending on the nature of nano-materials used, the radiation can be tuned across the ultraviolet, visible and infrared regions of the spectrum according to the requirement. The spectrum of emission is determined from the electron hole distribution in the nano-materials. LED is based on the electrical and optical properties of nano-materials used and they function by integrating the electrical and optical signals. LEDs are used in common lighting system, signal processing, indicator, light communication system, displays, optical-fibre communication system etc.

According to the design, LEDs are classified into types namely surface emitting diodes and edge emitting diodes. The surface emitting diode emits the light radiation spontaneously along the face parallel to the PN-junction and the light emitted along the opposite direction is either absorbed by the substrate or reflected back through metallic contacts. The edge emitting diode emits light radiation spontaneously along the edge of the PN-junction. The surface emitting diodes are more efficient because the spatial patterns of the emitted light depends on the geometries of the devices. The edge emitting diode has a narrow emission pattern which can be improved by using appropriate lenses. The schematic diagram of a surface emitting diode is shown in the figure-5.2(b).

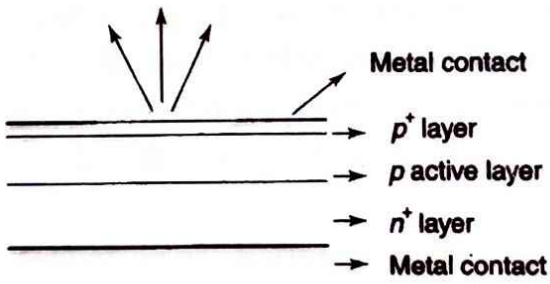


Fig.5.2(b) ***Schematic illustration of a surface emitting planar LED.***

The contact layer of the device must be heavily doped and very thin so that it can reduce the contact resistance and allows the light to pass through it. The absorption of light while passing through creates an additional loss to the optical signals. If an intrinsic or undoped active layer is sandwiched between P^+ and N^+ layers on either side then the charge carriers are transferred to the intrinsic layer from both the junctions. In practice the intrinsic layer becomes doped resulting with a PN-Junction and another high-low junction that contributes to charge transfer from both the junction. This causes electron-hole recombination and to prevent the surface recombination

the concept heterostructures was examined where higher bandgap heterostructured layers are constructed above and below the active layer by required doping. Due to the shift in bandgap and diffusion of the injected electrons and injected holes from the active layer is blocked.

In edge emitting LED the heterolayers are placed above and below the active layers. These layers alongwith the active layer act together in form of a waveguide. A super luminscent diode can now be produced by placing a highly reflective mirror at one end. The diode can also be arranged to act as a laser by placing two mirrors at both the ends then increasing the gain. The response time of LED is mostly between 2-10 ns. LED can be fabricated using nanoparticles, quantum dots, nanowires and thin films.

Nanoparticle LED

Nanoparticles are particles between 1 and 100 nanometres in size with a surrounding interfacial layer. The interfacial layer is an integral part of nanoscale matter and it affects all the properties of nanoparticles. The interfacial layer consists of ions, inorganic and organic molecules. Nanoparticles does not refer to individual molecule and it usually refers to an inorganic matter.

The efficiency of LED lighting can be increased by 50 percent by a technique in which metallic nanoparticles are prepared into semiconductors. In this technique the metal nanoparticle, can be grown both on and below the surface of semiconductors. The metal nanoparticles can enhance the efficiency of LED in several ways. They can act as tiny antennas that alter and redirect the electricity running through the semiconductor, tuning more of it into light. They can also help in reflecting light out of the device and prevent it from being trapped inside and wasted.

This technique can be used with the gallium nitride which is used in LED lighting to boost its efficiency. This process can also be used in other semiconductor products, including solar cells to boost the efficiency.

In other technique the cost of LED can be reduced by manufacturing the LED with silicon based nanoparticles. The silicon based nanoparticles soften the blue light emitted by LED, creating white light.

Quantum dot LED :

Quantum dots are semiconductor nanocrystals with optical properties that let their emission colour to be tuned from the visible light into the infrared spectrum. This allows LED fabricated with quantum dots, to produce any colour. This provides more colour options and better colour rendering than white LED because the emission spectrum is much narrower characteristic of quantum confined states.

There are two types schemes for the excitation of quantum dot (QD). The first scheme uses photo excitation with a primary light source LED. The second scheme is direct electrical excitation. The photo excitation scheme is a technique in which a blue LED is coated with quantum dots and it glows white in response to the blue light emitted from LED. This method emits a warm yellowish-white light. QDs can also be used for use in white LED.

Quantum dots can be synthesized for LED applications and a light converter can be built on their basis to convert efficiently the blue light to any colour. Such QDs are used to emit visible or infrared light of any wavelength.

In QDLED a layer of quantum dots is sand wiched between layers of electron transporting and hold transporting materials. An applied electric field causes electrons and holes to move into the quantum dot layer and recombining an exciton that excites QD. An exciton is a bound state of an electron and a hole which are attracted to each other by the electrostatic force. It is an electrically neutral quasi-particle that exists in semiconductor. It is regarded as an elementary excitation of condensed matter that can transport energy without transporting net electric charge. An exciton is formed when a photon is absorbed by a semiconductor. This excites an electron and it jumps from valence band to conduction band. This leaves positively charged hole. The electron in the conduction band is attracted to hole by coulomb force. Consequently an exciton is formed.

Nanowire LED

Nanowire is a nanostructure with the order of a nanometre (10^{-9}m). The ratio of length to width of a nanowire, is more than 1000. It is a structure having a thickness or diameter constrained to tens of nanometres or less and it has an unconstructed length. At nanoscale quantum mechanical effects are important. Nanowire is also known as quantum wire. There are different types of nanowires such as superconducting nanowire (YBCO), metallic nanowires (Ni, Pt, Au), semiconducting nanowires (SiN, W, GaN), insulating nanowires (SiO_2, TiO_2) and molecular nanowires (DNA).

Nanowires are referred to a one dimensional (1 – D) materials. In nanowires electrons are quantum confined laterally and occupy energy levels that are different from the traditional continuum of energy levels or bands found in bulk materials.

Nanowire LED can be manufactured by fabricating an LED resembling transistor that consists of an iridium-nitride nanowire stretched between two electrodes on top of a silicon substrate. This nanowire is about 100 nm wide and spans a distance of less than 10 μm. The nanowire emits light due to the application of current. Nanowire LED is more efficient and has an improved performance. It can emit infrared light.

In nanowire LED only electrons are injected. This causes formation of electron and holes inside the nanowires. This mechanism is more efficient because a single electron can be used to generate more than one electron-hole pair. Nanowire LED can emit more intense light than other LED. It extends the range of colours that can be emitted from nitride based nanowire. Nanowire LED has a peculiar ability to emit more intense light as the temperature increases. Hence nanowire LED can withstand high temperatures. This property of nanowire LED could be useful for certain military applications.

Thinfilm LED

Thinfilm is a layer of material ranging from fractions of nanometre to several micrometres in thinkness. Thinfilm LED can be fabricated by bonding the LED structure to metalized carrier

substrate and after which the original epitaxial growth substrate is removed. This is achieved by thin-film technology. Thinfilm LED has an extremely high luminous efficacy. Thinfilm LED consumes less electric power and it has lower cost.

5.3 SOLAR CELL

Solar cell is made up of semiconductor PN-Junction which helps in the conversion of solar radiation into electricity. This conversion of sunlight into electricity is based on photovoltaic effect. Photovoltaic effect is the generation of potential difference at the junction of the different materials due to the incident of light radiation. Solar cells can be fabricated using nanoparticles, quantum dots, nanowires and thin films.

Nanoparticle Solar Cell

Nanoparticle solar cell can be fabricated using nanoparticles. It has lower manufacturing cost and installation cost. Dyesensitized solar cell is a nanoparticle solar cell. It is made up of the ceramic titanium dioxide (titania), electrolyte and electrodes. The electrodes are coated with a thin transparent and conductive film composed of fluorine doped tin dioxide on glass. The dye molecules are established on titanium dioxide to construct the photo sensitized anode. When sunlight is absorbed by the dye molecules, excitons are produced in the dye molecules. These excitons are then passed through the nanomaterial titanium dioxide to the outer circuit. This constitute a current. The electrolyte ensures the regeneration of excitons from the dye molecules.

Quantum dot Solar Cell :

Quantum dot solar cell is fabricated using quantum dots. In quantum dot solar cell the quantum dots absorb sun light to generate excitons. It is also based on photovoltaic effect. It has lower cost. The larger dipole moments and enhanced charge carrier separation are the advantages of quantum dots. Quantum dots solar cells based on lead sulphide systems are the most used solar cells. The bandgap tunability of such solar cell can be extended to cover the far infrared region of the solar spectrum. These quantum dots can easily be synthesized through solution synthesis and hence they can be readily transferred over the desired substrate through spin coating. These quantum dots can also be implemented in single junction solar cell to absorb the solar radiation and convert them into electricity.

Nanowire Solar Cell :

Nanowire solar cell is fabricated using semiconductor nanowires. In nanowire solar cell the nanowires absorb the solar radiation to generate excitons. Nanowire solar cell has high power conversion efficiency. The conversion of solar radiation into electricity is based on photovoltaic effect. Recently semiconductor nanowires have received great interest for their potential applications to solar cells. Silicon nanowire (SiNW) can be used for the fabrication of a nanowire solar cell.

Thin film Solar Cell :

Thin film solar cell is made by depositing one or more thin layers or thin film of photovoltaic material on a substrate such as glass or plastic or metal. Amorphous thin film silicon, (a – Si, TF

– Si), cadmium telluride (Cd Te) and copper indium gallium diselenide (CIGS) are used in the fabrication of thin film solar cells. Thin film solar cell is much thinner than crystalline solar cell. It is flexible and it has lower weight. It is used in solar panels. It is cheaper. It is less efficient than crystalline solar cell.

5.4 SINGLE ELECTRON DEVICES

Sinlge electron devices are the devices which are based on the controllable single electron transfer between small conducting small metal spheres (islands). In 1909, Millikan first illustrated the manipulation of single electron, but the single electron devices cannot be implemented in solid state circuit till 1980 due to limited fabrication techniques. In recent years single electron device have been applied in several important experiments and are feasible in unique scientific instrumentation. Examples of sinlge electron devices are single electron box, single electron transisor and single electron trap.

Basic Physics of SED :

Let the net charge of an island (Fig-5.4(a)) is zero.

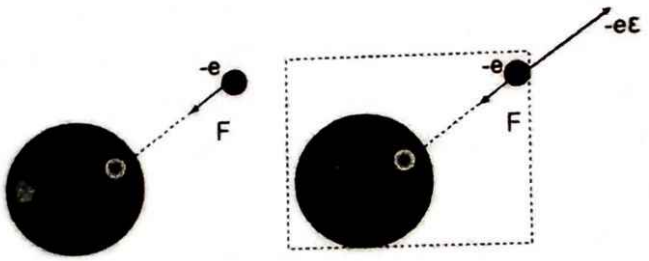


Fig. 5.4(a) : An island (A small metal sphere)

In this state there is no electric field beyond the border of the island. If an external force F brings a sinlge electron (–e) from outside to a point close to island then an electric field $\left(\varepsilon = \frac{F}{-e}\right)$ is produced by the non-zero net charge.

The electric field is inversely proportional to the square of the island size.

Hence the electric field becomes very strong for nanoscale structure.

Charging energy E_c is more accurate measurement on this charge effect than electric field. Since the island size is comparable to the de Broglie wavelength of the electron island, the energy scale is described by electron addition energy E_a, the sum of charging energy E_c and the quantum kinetic energy of the added electron E_k. E_c should be dominant of E_a to reduce the thermal fluctuation impacts on E_k. Thermally induced random tunnelling events can be avoided when the digital single-electron devices operates at room temperature and it requires E_a eV and minimum feature size ~ 1 nm.

Orthodox Theory

According to orthodox theory of single electron tunnelling, a single electron randomly tunnels through a particular tunnel barrier with a certain rate Γ, which depends on the electrostatic energy of the system as a result of this tunneling as shown in Fig. 5.4(b).

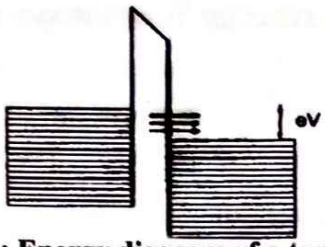


Fig. 5.4(b) : Energy diagram of a tunnel junction

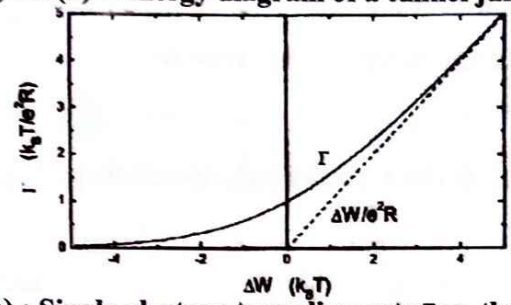


Fig. 5.4(c) : Single-electron tunneling gate Γ vs. the electrostatic energy loss ΔW, R is the resistance of the tunnel barrier, e is electron charge and k_B is Boltzmann constant, T is temperature

This is because the rate Γ is proportional to the number of occupied quantum states in the electron source. Fig. 5.4(c) shows the graph between single electron tunneling rate Γ and the electrostatic energy loss ΔW.

Single Electron Box :

Single electron box is conceptually the simplest single electron device. The schematic diagram of a single electron box is shown in the Fig-5.4(d). It consists of a small island which is separated from a large source elelctrode by tunnel barrier. Gate is another electrode, which is used to apply an external electric field on the small island. Electron tunnelling effects occur through the tunnel barrier, when the electro-chemical potential of the island is changed by the external electric field E.

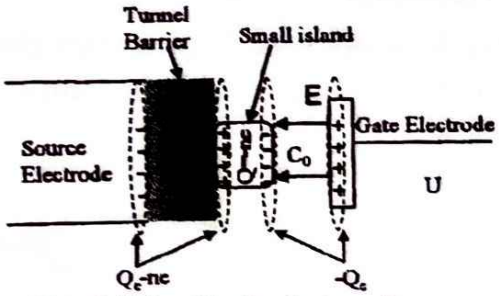


Fig. 5.4(d) : Single electron box

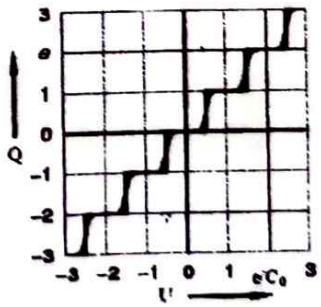


Fig. 5.4(e) : Island charge Q (= -ne) as a function of gate voltage.
Blue : at vanishing small temperature transition between states differing in the island charge by a single electron are sharp.
Red : at elevated temperatures the steps are thermally broadened

The Gibb's free energy W of the system is given by

$$W = \frac{Q^2}{2C_\Sigma} + \frac{C_0 QV}{C_\Sigma} + \text{constant} \quad \text{.....(1)}$$

The island charge Q is given by .....(2)

$$Q = ne - Q_e$$

The external charge Q_e is given by .....(3)

$$Q_e = V C_0$$

Where C_0 is the island gate capacitance, C_Σ is the total capacitance and V is the applied gate voltage.

The increasing gate voltage causes more electrons on the island. The graph between island change Q and gate voltage V is shown in the Fig. 5.4(e).

The single electron box has the following disadvantages :

(i) It can not store information because the charge stored in the island is a function of applied gate voltage.

(ii) It is difficult to measure the charge state of single electron box because no DC current carried in the box.

Single Electron Transistor :

Single electron transistor is the simplest single electron device in which the effect of Coulomb blockade can be observed. The schematic diagram of a single electron transistor is shown in the Fig-5.4 (f).

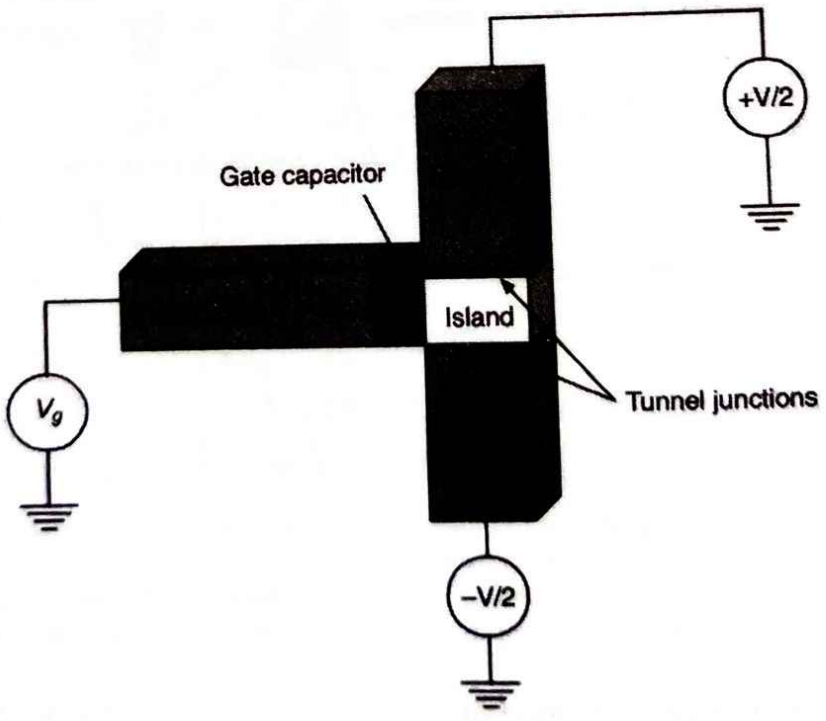
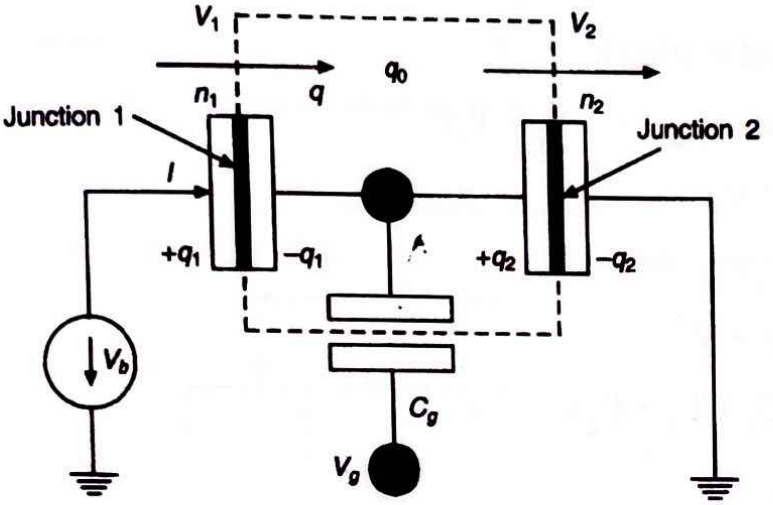


Fig. 5.4(f) Schematic structure of a 'metallic' single electron transistor.

It consists of two electrodes known as source and drain connected through tunnel junctions to one common electrode with a low capacitance, known as island. The electrical potential of the island can be tuned by another electrode known as gate, which is capacitively coupled to the island. The circuit diagram of a SET is shown in the Fig-5.4(g).



(a)

Fig. 5.4(g) : Circuit diagram of a SET

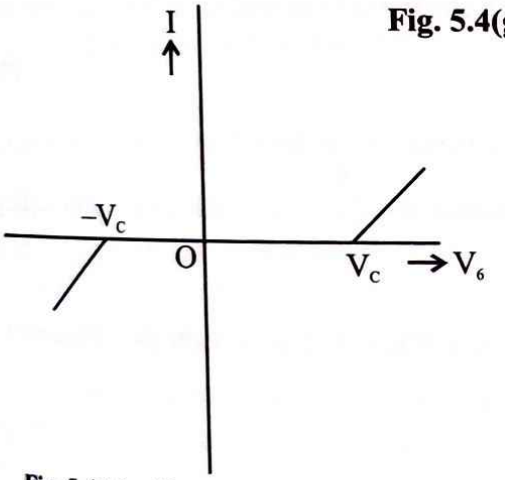


Fig. 5.4(h) – V ~ I Curve of SET

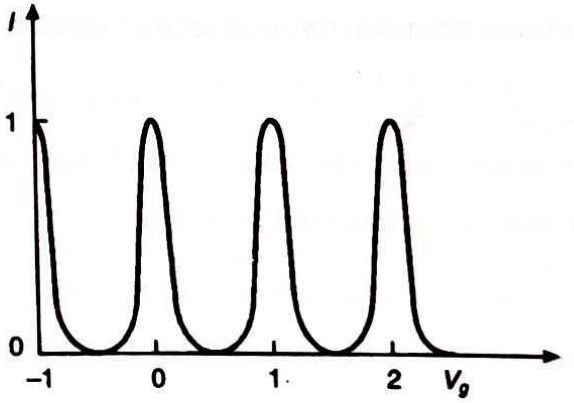


Fig. 5.4(i) : Coulomb oscillations in a single-electron transistor

Case-1 : Let the gate voltage V_g is zero. If the bias voltage V_b is less than the Coulomb blockade, $V_C = \frac{e}{C_\Sigma}$ then no electron can tunnel through the two tunnel junctions because there is not sufficient energy to charge the island. This effect is known as Coulomb blockade.

If the bias voltage V_b is greater than the Coulomb blockade V_C then current will flow through the circuit as shown in the Fig 5.4 (h).

The charge contained in the whole island is given by

$$q = -q_1 + q_2 + q_0 = -ne + q_0 \qquad .....(1)$$

Where q_0 is the background charge, which is non-integer and resulted from the impurity and e is the charge of an electron.

Case-II : Let the gase voltage V_g is not zero. The charge in the whole island is modified by the gate voltage V_g and is given by

$$q = -ne + q_0 + C_g(V_g - V_2) \quad \text{.....(2)}$$

where $q_1 = C_1 V_1$ .....(3)

$$q_2 = C_2 V_{32} \quad \text{.....(4)}$$

$$V_b = V + V_2 \quad \text{.....(5)}$$

$$C_\Sigma = C_1 + C_2 + C_g \quad \text{.....(6)}$$

$$n = n_1 - n_2 \quad \text{.....(7)}$$

Where n_1 is the number of electrons tunneled through first junction and n_2 is the number of electrons tunneled through second junction.

If the gate voltage V_g is increased and the bias voltage V_b is less than the Coulomb blockade then the current will oscillate with a periode of $\frac{e}{C_g}$. These are Coulomb oscillations shown in Fig. 5.4(i).

Single electron transistor can be viewed as a field effect transistor in which the channel is replaced by two tunnel junctions forming a metallic island.

Single Electron Trap :

Single electron trap is an SED which has more than two tunnel junctions in the island, which is separated by tunnel barriers. Single electron trap operates like an internal memory and it can store two or more bits of information by changing gate voltage V_g applied on the island of the device. The schematic diagram of a single electron trap is shown in the Fig-5.4(j).

Initially the gate is provided with a sufficiently high gate voltage V^+ and the electrons are driven into the edge of island. Now V_g is decreased to the initial level and the electrons are trapped in the island. If the voltage is reduced further then the electrons can be removed from the trap. Static characteristics of a single electron trap are shown in the Fig-5.4(k).

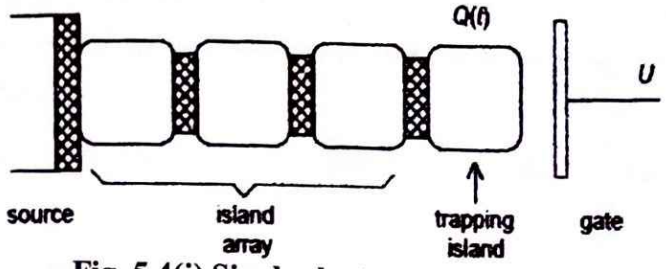
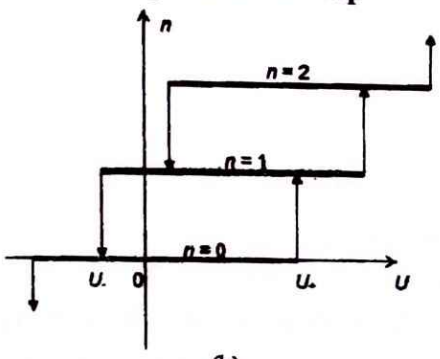


Fig. 5.4(j) Single electron trap



(b)

Fig. 5.4(k) Static characteristics of the device

5.5 CARBON NANOTUBE

Carbon nanotube (CNT) is an allotrope of carbon. There are two types of CNT namely single walled carbon nanotube (SWNT) and multi-walled carbon nanotube (MWNT). Single walled carbon nanotube (SWNT) is a one thick sheet of graphite (graphene) rolled up into a seamless cylinder with diameter of the order of a nanometer. In SWNT the length to diameter exceeds 1,000000. Multi-walled carbon nanotube (MWNT) is made up of a number of concentric tubes.

These carbon nanotubes have novel properties that make them potentially useful in many applications in nanotechnology, electronics, optics and other fields. They also show extra-ordinary strength and unique electrical properties and are efficient conductors of heat.

The schematic diagram of the formation of different types of nanotubes is shown in the Fig-5.5(a).

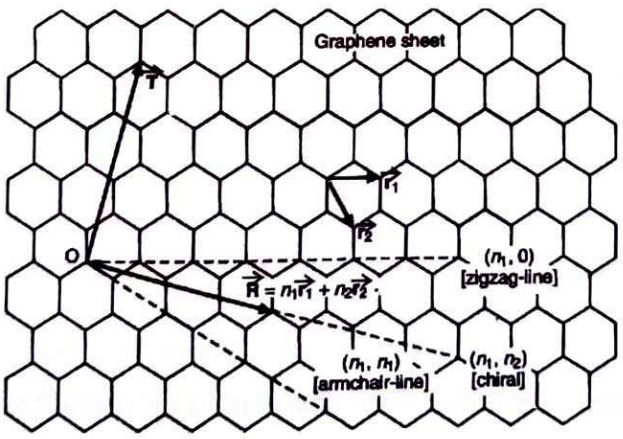


Fig. 5.(a) : Schematic illustration of the formation of different types of nanotubes.

The choice of rolling axis relative to the hexagonal network of graphene sheet and radius of the closed cylinder allows for the different types of SWNTs, which may vary from insulator to conductor. The way in which the graphene sheet is wripped is represented by a pair of indices (n_1, n_2) called the chiral vector which is represented by the unit vectors $\vec{r}_1$ and $\vec{r}_2$.

$$\therefore \vec{R} = n_1 \vec{r}_1 + n_2 \vec{r}_2$$

Where the integers n_1 and n_2 denote the number of vectors along two directions in the honeycomb crystal lattice of graphene.

There are two line, represented by dotted lines across the graphene sheet -

(i) One along the horizontal zigzag bonds and is called zigzag line.

(ii) The other travelling across each hexagon and is called the armchair line.

If $n_2 = 0$ then the vector $\vec{R}$ coincides with the zigzag line and here the vector $\vec{T}$ is perpendicular to the zigzag line. If the graphene sheet is rolled over the zigzag line towards the direction of $\vec{T}$ then the nanotube is called zigzag nanotube. The schematic diagram of zigzag nanotube structure is shown in the Fig-5.4(b).

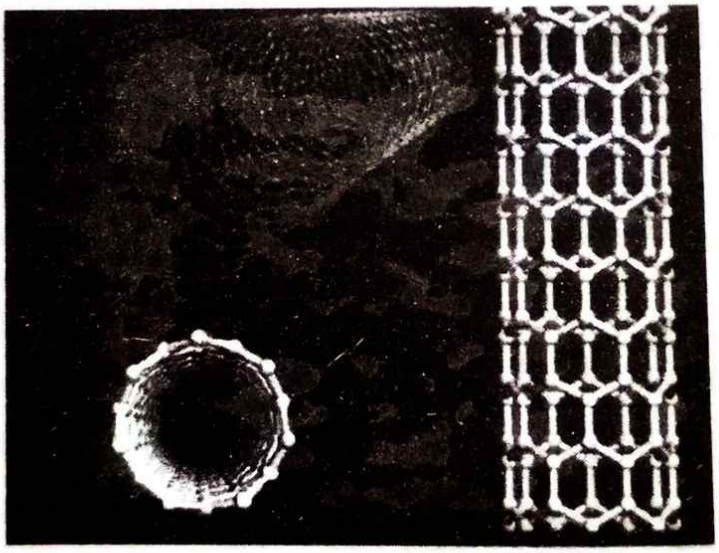


Fig.5.4(b) : Schematic diagram of zigzag nanotube structure

If $n_1 = n_2$ then the vector $\vec{R}$ falls on the armchair line and here the vector $\vec{T}$ is perpendicular to the armchair line. If the graphene sheet is rolled over armchair line towards the direction of $\vec{T}$ then the nanotube is armchair nanotube. The schematic diagram of armchair nanotube structure is shown in the Fig-5.4(c).

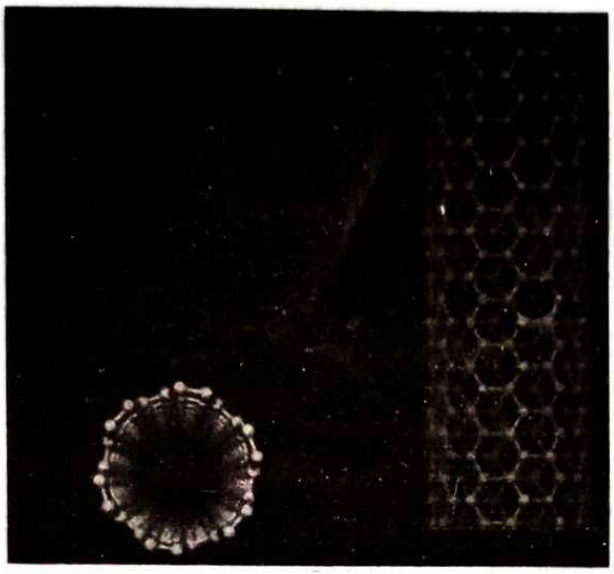
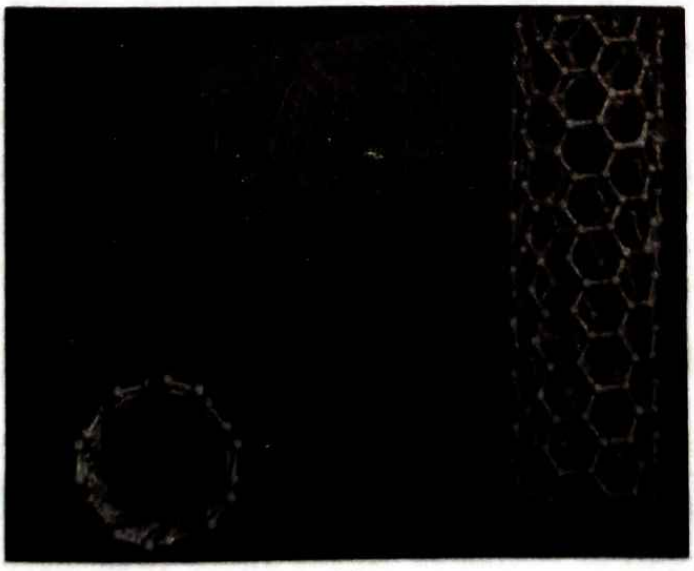


Fig.5.4(c) : Schematic diagram of armchair nanotube structure

In $n_1 \neq n_2$ then the vector $\vec{R}$ will be directed along any arbitrary direction defined by the magnitudes of n_1 and n_2. If the graphene sheet is rolled along this arbitrary direction then the nanotube is called chiral nanotube. The schematic diagram of chiral nanotube structuer is shown in the Fig-5.5(d). The void spaces in these carbon nanotubes vary with different values of n_1 and n_2.



(c)

Fig.5.4(d) : Schematic diagram of chiral nanotube structure

The schematic diagram of a multi-walled nanotube (MWNT) is shown in the Fig-5.5(e).

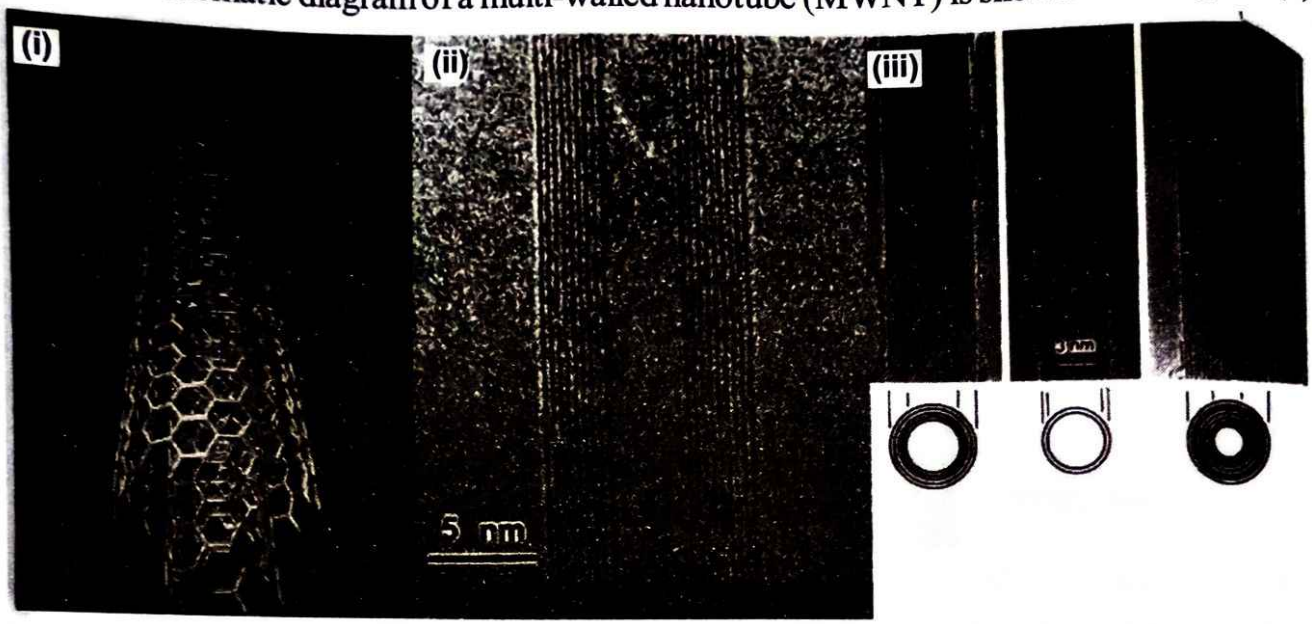


Fig.5.5(e) **(i)** Schematic diagram of a multi-walled CNT, a concentric cylindrically nested assembly of nanotubes, **(ii)** TEM image of an actual nine-walled nanotube, and **(iii)** TEM images of 5, 2 and 7-walled nanotube.

Carbon nanotubes exhibit varying electrical properties depending on the way the graphene sheet sprials around the tube and other factor like doping, and they can be superconducting, insulating, semiconducting or conducting. The conductivity of CNTs can vary from conducting to semiconducting to insulating depending on the chirality of the nanotubes. It is observed that the armchair nanotubes are metallic, chiral nanotubes are low conduting or semiconducting and zigzag nanotubes are semi-metallic to semiconducting.

Carbon nanotubes are self-assembled structures that formed under various controlled conditions such as carbon arc discharge, laser ablation, chemical vapour deposition based on hydrocarbon gases etc. The smallest diameter CNT has been observed to be 0.5 nm, that has been grown in zeolite cavities.

5.6 CNT BASED TRANSISTORS

CNT based transistors are the transistors in which carbon nanotubes are used. Carbon nanotube field effect transistors (CNTFET) are CNT based transistors and are similar to MOSFET of today. CNTFETs require three terminals namely source, drain and gate. In CNTFET carbon nanotubes are used as channel material but in MOSFET heavily doped silicon is used as channel material, CNTFETs are of two types namely N-channel CNTFET and P-channel CNTFET.

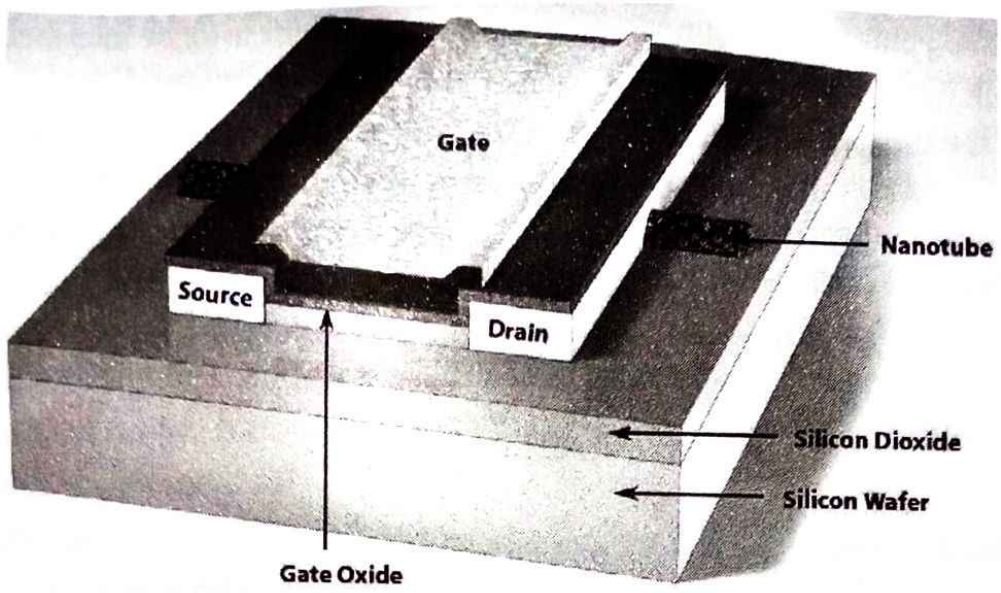


Fig. 5.6 (a) diagram of a CNTFET

The diagram of a CNTFET is shown in the Fig-5.6(a). The gate is placed on the top of the carbon nanotube. The gate is separated from the nanotube by an insulator such as gate oxide which is much thinner atout 15 nm. The nanotube is sealed so that air will not cause the CNTFET to act as P-channel CNTFET.

P-Channel CNTFET

P-channel CNTFET conducts holes when a negative voltage is applied on the gate. It does not conduct electrons even at high positive gate voltage.

The following procedure is used to create a P-channel CNTFET.

(i) Single crystal Si substrates are cleaned and coated with 120 nm of SiO_2.
(ii) Single walled carbon nanotubes (SWNT) are produced by laser ablation or CVD.
(iii) Nanotubes are cleaned and untangled by sonication.
(iv) Nanotubes are diluted with 1, 2 - dichloethane solution and density of solution is adjusted to yield one nanotube per a given area.
(v) Solution is spun onto the substrate.
(vi) Placement of nanotubes are confined using AFM or SEM.
(vii) Metal source and drain electrode are created by using e-beam lithography and lift off.
(viii) Samples are annealed at 850° for 100 seconds and metal carbide is formed at the carbon nanotube and metal junctions and hence contact resistance is reduced.
(ix) A mixture of SiH_4 and O_2 is deposited at 300°C to create gate oxide.
(x) Source and drain contact holes are opened in the new oxide layer.
(xi) Annealing is done at 600°C in N_2 for 30 minutes to densify the oxide.

(xii) Gate electrode is patterned using e-beam lithography and lift-off with 50 nm of gate metal.

(xiii) Gas forming annealing is done to reduce trapped charges in oxide interface.

The result is a P-channel CNTFET and nanotubes become P-types when they are exposed to air because the oxygen in the air causes the Fermi-level at the contacts to shift closer to the valence band. The result is that the holes are able to tunnel through a small barrier but the electrons are not able to tunnel through a very large barrier. The band structure at the contact for P-channel CNTFET is shown in the Fig-5.6(b).

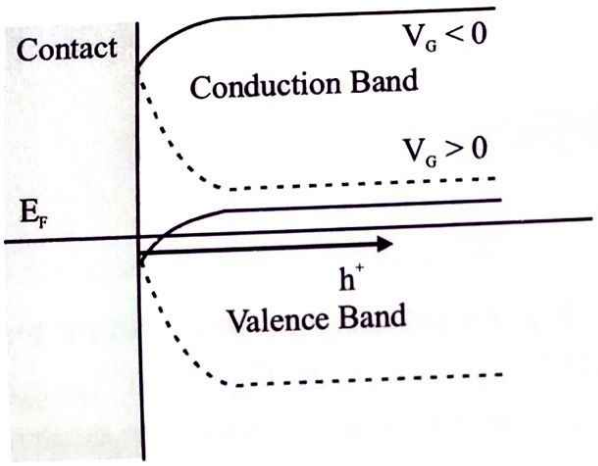


Fig. 5.6(b) : Band structure at the contact for P-channel CNTFET

Transfer characteristic is the curve between drain current (I_d) and gate to source voltage (V_{gs}) at constant drain to source voltage (V_{ds}). Transfer characteristics of P-channel CNTFET at $V_{ds} = -0.6$ V is shown in the fig.5.6 (c).

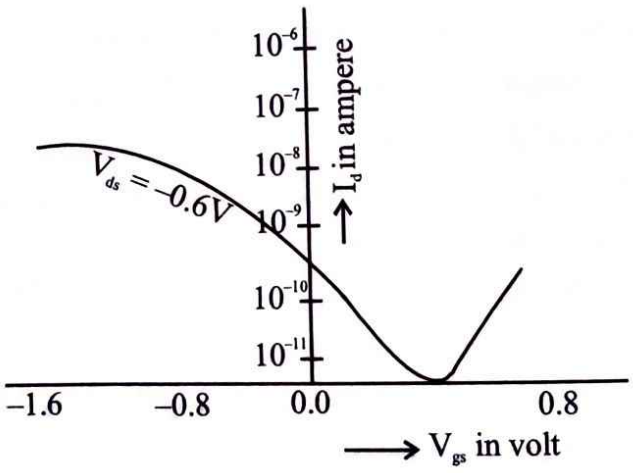


Fig. 5.6(c) Transfer characteristics of P-channel CNTFET

From the transfer characteristic it is clear that there is a little bit conduction when the gate to source voltage is positive, however this conduction is too small to turn on another transistor. If the gate to source voltage is negative then the transistor is turned on and causes the increase in drain current.

N-Channel CNTFET

N-Channel CNTFET conducts electrons when a positive voltage is applied on the gate. It does not conduct holes even at high positive gate voltage.

N-Channel CNTFET can be created by two ways. One is annealing and the other is doping.

Annealing

Annealing is done to drive out the oxygen that was absorbed while the nanotube was exposed to air.

(i) Single crystal Si substrates are cleaned and coated with 120 nm of SiO_2.
(ii) Single walled carbon nanotubes (SWNT) are produced by laser ablation or CVD.
(iii) Nanotubes are cleaned and untangled by sonication.
(iv) Nanotubes are diluted with 1, 2 - dichloethane solution and density of solution is adjusted to yield one nanotube per a given area.
(v) Solution is spun onto the substrate.
(vi) Placement of nanotubes are confined using AFM or SEM.
(vii) Metal source and drain electrode are created by using e-beam lithography and lift off.
(viii) Samples are annealed at 850° for 100 seconds and metal carbide is formed at the carbon nanotube and metal junctions and hence contact resistance is reduced.
(ix) Annealing is done at 450°C in N_2 to remove absorbed oxygen.
(x) A mixture of SiH_4 and O_2 is deposited at 300°C to create gate oxide.
(xi) Source and drain contact holes are opened in the new oxide layer.
(xii) Annealing is done at 600°C in N_2 for 30 minutes to densify the oxide.
(xiii) Gate electrode is patterned using e-beam lithography and lift-off with 50 nm of gate metal.
(xiv) Gas forming annealing is done to reduce trapped charges in oxide interface.

The Fermi-level is shifted up towards the conduction band and the barrier for the electrons is reduced by removing the oxygen. This will allow the electrons to tunnel through the reduced barrier. At the some time the barrier for the holes is increased and hence the holes will not be able to tunnel through the increased barrier. The result is an N-channel CNTFET and the nanotubes become N-types. The band structure at the contact for N-channel CNTET is shown in the Fig-5.6(d) flows when the gate to source voltage is negative. If the gate to source voltage is positive then drain current rapidly increases.

Doping

Doping occurs with an electron donor such as potassium. The following procedure is used to create an N-channel CNTFET by doping.

(i) Single crystal Si substrates are cleaned and coated with 120 nm of SiO_2.
(ii) Single walled carbon nanotubes (SWNT) are produced by laser ablation or CVD.
(iii) Nanotubes are cleaned and untangled by sonication.

(iv) Nanotubes are diluted with 1, 2 - dichloethane solution and density of solution is adjusted to yield one nanotube per a given area.
(v) Solution is spun onto the substrate.
(vi) Placement of nanotubes are confined using AFM or SEM.
(vii) Metal source and drain electrode are created by using e-beam lithography and lift off.
(viii) Samples are annealed at 850° for 100 seconds and metal carbide is formed at the carbon nanotube and metal junctions and hence contact resistance is reduced.
(ix) Nanotube is doped with an electron donor such as potassium.
(x) A mixture of SiH_4 and O_2 is deposited at 300°C to create gate oxide.
(xi) Source and drain contact holes are opened in the new oxide layer.
(xii) Annealing is done at 600°C in N_2 for 30 minutes to densify the oxide.
(xiii) Gate electrode is patterned using e-beam lithography and lift-off with 50 nm of gate metal.
(xiv) Gas forming annealing is done to reduce trapped charges in oxide interface.

The doping causes the coumlomb blockade to shift downwards and the Fermi level is pined down by the doping and does not move. The band structure at the contact for N-channel CNTFET created by doping, is shown in the Fig-5.6(e).

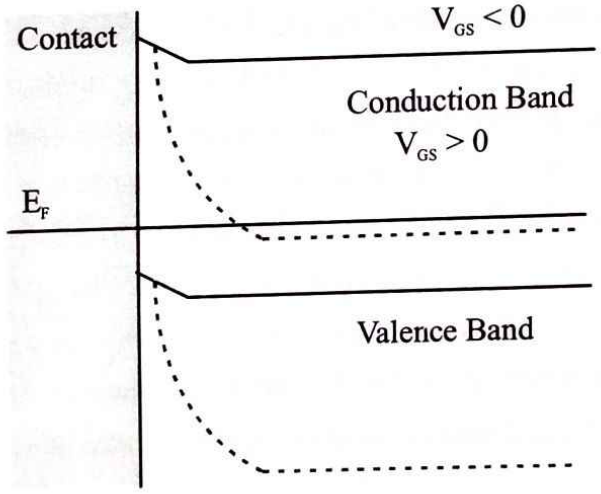


Fig. 5.6(e) : Band structure at the contact for N-channel CNTFET

Transfer characteristic of N-channel CNTFET for $V_{ds} = 0.5$ V is shown in the Fig-5.6(f).

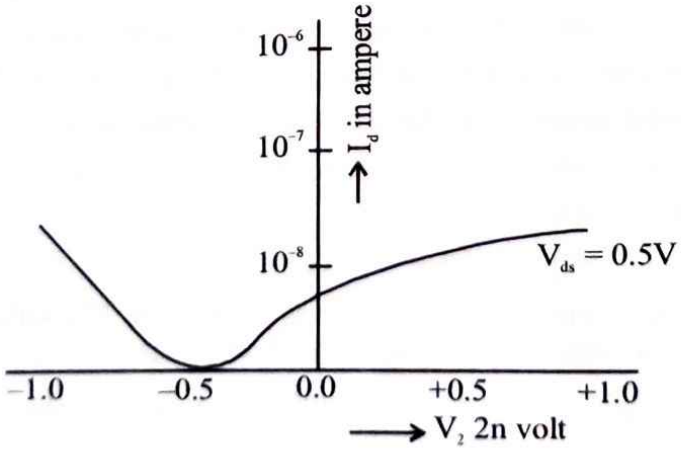


Fig. 5.6(f) : Transfer characteristics of N-channel CNTFET

From the transfer characteristic is clear that small drain current decreases to zero for V_g = – 0.5 volt and increases with the increase in the value of V_g.

SUMMARY

- Nano-materials are the materials that are processed in the nanoscale.
- Nano-materials are different from other materials because nano-materials have a massive surface area.
- Nanoparticles are extremely reactive compared to their larger form because nano-materials have very high surface area.
- Carbon nanotube (CNT) is a nano-material application.
- Carbon nanotubes have a very high strength due to the higher surface area of its originating materials.
- In the nano-level quantum effects have a higher effect on the behaviour of particles.
- The magnetic, electrical and optical properties can be effectively exploited to certain applications.
- Thin films and engineered surfaced fall in to the one dimensional applications of nano-materials.
- Nanotubes and nanowires fall in to the two dimensional applications of nano-materials.
- Nanowires are ultrafine wires or linear arrays of dots that are formed self-assembly.
- Semiconductor nanowires are proudced by silicon.
- Nanodots and nano-particles like dendrimers and fullermes fall into the three dimensional applications of nano-materials.
- Dendrimers are spherical polymeric molecules that are formed through a nanoscale self-assembly process.
- Photonic devices are the electronic devices for creating, manipulating or detecting light.
- Photonic devices are less sensitive to interference.
- Light emitting diode (LED), photo diode, laser diode and solar cells are examples of photonic devices.
- Light emitting diode (LED) emits light spontaneously and it is constructed through a semiconductor PN-junction.
- LED is based on the electrical and optical properties of nano-materials used and they function by integrating the electrical and optical signals.
- LEDs are used in common lighting system, signal processing, indicator, light communication system, displays, optical-fibre communication system etc.
- The surface emitting diode emits the light radiation spontaneously along the face parallel to the PN-junction and the light emitted along the opposite direction is either absorbed by the substrate or reflected back through metallic contacts.

- The edge emitting diode emits light radiation spontaneously along the edge of the PN-junction.
- The surface emitting diodes are more efficient because the spatial patterns of the emitted light depends on the geometries of the devices.
- The edge emitting diode has a narrow emission pattern which can be improved by using appropriate lenses.
- In edge emitting LED the heterolayers are placed above and below the active layers.
- LED can be fabricated using nanoparticles, quantum dots, nanowires and thin films.
- Nanoparticles are particles between 1 and 100 nanometres in size with a surrounding interfacial layer.
- The efficiency of LED lighting can be increased by 50 percent by a technique in which metallic nanoparticles are prepared into semiconductors. In this technique the metal nanoparticle, can be grown both on and below the surface of semiconductors.
- Quantum dots are semiconductor nanocrystals with optical properties that let their emission colour to be tuned from the visible light into the infrared spectrum.
- In QDLED a layer of quantum dots is sand wiched between layers of electron transporting and hold transporting materials.
- Nanowire is a nanostructure with the order of a nanometre (10^{-9}m).
- Nanowire LED can be manufactured by fabricating an LED resembling transistor that consists of an iridium-nitride nanowire stretched between two electrodes on top of a silicon substrate.
- Thinfilm is a layer of material ranging from fractions of nanometre to several micrometres in thinkness.
- Thinfilm LED can be fabricated by bonding the LED structure to metalized carrier substrate and after which the original epitaxial growth substrate is removed.
- Solar cell is made up of semiconductor PN-Junction which helps in the conversion of solar radiation into electricity.
- Solar cells can be fabricated using nanoparticles, quantum dots, nanowires and thin films.
- Nanoparticle solar cell can be fabricated using nanoparticles.
- Dyesensitized solar cell is a nanoparticle solar cell. It is made up of the ceramic titanium dioxide (titania), electrolyte and electrodes.
- In quantum dot solar cell the quantum dots absorb sun light to generate excitons.
- Nanowire solar cell is fabricated using semiconductor nanowires.
- Nanowire solar cell has high power conversion efficiency.
- In nanowire solar cell the nanowires absorb the solar radiation to generate excitons.
- Thin film solar cell is made by depositing one or more thin layers or thin film of photovoltaic material on a substrate such as glass or plastic or metal.

- Thin film solar cell is much thinner than crystalline solar cell.
- Sinlge electron devices are the devices which are based on the controllable single electron transfer between small conducting small metal spheres (islands).
- Single electron box is conceptually the simplest single electron device.
- The single electron box has the following disadvantages :

(i) Single electron box can not store information because the charge stored in the island is a function of applied gate voltage.

(ii) It is difficult to measure the charge state of single electron box because no DC current carried in the box.

- Single electron transistor is the simplest single electron device in which the effect of Coulomb blockade can be observed.
- Single electron transistor can be viewed as a field effect transistor in which the channel is replaced by two tunnel junctions forming a metallic island.
- Single electron trap is an SED which has more than two tunnel junctions in the island, which is separated by tunnel barriers.
- Single electron trap operates like an internal memory and it can store two or more bits of information by changing gate voltage V_g applied on the island of the device.
- Carbon nanotube (CNT) is an allotrope of carbon.
- Carbon nanotubes have novel properties that make them potentially useful in many applications in nanotechnology, electronics, optics and other fields.
- The conductivity of CNTs can vary from conducting to semiconducting to insulating depending on the chirality of the nanotubes.
- The armchair nanotubes are metallic, chiral nanotubes are low conduting or semiconducting and zigzag nanotubes are semi-metallic to semiconducting.
- Carbon nanotubes are self-assembled structures that formed under various controlled conditions such as carbon arc discharge, laser ablation, chemical vapour deposition based on hydrocarbon gases etc.
- The smallest diameter CNT has been observed to be 0.5 nm, that has been grown in zeolite cavities.
- CNT based transistors are the transistors in which carbon nanotubes are used.
- Carbon nanotube field effect transistors (CNTFET) are CNT based transistors and are similar to MOSFET
- CNTFETs require three terminals namely source, drain and gate.
- In CNTFET carbon nanotubes are used as channel material but in MOSFET heavily doped silicon is used as channel material.
- P-channel CNTFET conducts holes when a negative voltage is applied on the gate. It does not conduct electrons even at high positive gate voltage.
- N-Channel CNTFET conducts electrons when a positive voltage is applied on the gate. It does not conduct holes even at high positive gate voltage.

CHAPTER 6

NANOMATERIAL DEVICES

LEARNING OBJECTIVES

- Introduction, Quantum dot heterostructure laser.
- Optical switching, Optical data storage.
- Magnetic quantum well, Magnetic quantum dots.
- Magnetic data storage, Micro electro-mechanical systems.
- Nano electromechanical systems.

6.0 INTRODUCTION

Nanomaterials are used widely in various fields. Bulk nanomaterials are used in hard coatings, fabrication of components for the aeronautic industry, cars, ducts in petroleum and gas industries, anticorrosion applications and sports sector. Quantum dots are semi-conducting nanocrystals when illuminated with UV light, emit a vast spectrum of bright colours that can be used to identity cells and other biological activities. Quantum dots are used in optoelectronis and manufacturization of inks and paints for anti-counterfeit tagging. Nanotubes and nanowires are used to prepare nanocomposites for electronic applications such as solar cell, LED, photo-detector etc. Nanometals are used to establish conducting screens, sensors and energy materials. They are also used for 'antibacterial and catalysis functions. Fullernes are used in sports and cosmetic sectors. Dendrimers are used in medical applications for administration of medicines, diagnostics and therapeutics. Nanoporous materials are used in aerogels to generate the required thermal insulation in opto electronic applications and they are also used in biomedical applications for drug carriers and implants. Nanoceramics are used in anti-UV components and photo-catalytic studies. They are also used in the mechanochemical polishing of silicon wafers for the electronic industries.

Nanomaterials are used in electronic, magnetic, optoelectronic, biomedical, pharmaceutical, cosmetic, energy, catalytic and materials applications, Heterojunction lasers, optical switching, optical data storage, magnetic data storage, micro electro-mechanical system (MEMS), nano electro-mechanical system (NEMS) are some applications of nanomaterials.

6.1. QUANTUM DOT HETEROSTRUCTURE LASER

A quantum dot is a semiconductor nanostructure that confines the motion of conduction band electrons valence band holes or excitons in all three spatial directions. It emits light if electricity or light is applied. Larger quantum dots emit lights of longer wavelengths and smaller quantum dots emit lights of smaller wavelengths. Lasers are the potential applications of quantum dots.

Heterostructure is the combination of multiple heterojunctions together in a device. Heterojunction is the interface between two layers of dissimilar crystalline semiconductors having unequal band gaps. Lasers are the potential applications of heterostructure.

A quantum dot heterostructure is a semiconductor laser that uses quantum dots heterostructure as the active laser medium in its light emitting region.

In 1963 Herbert Kroemer proposed heterostructure lasers. He suggested that population inversion could be greatly enhanced by heterostructures. He said that by incorporating a smaller direct band gap material such as GaAs between two larger band gap layers such as A*l* As, carriers can be confined so that lasing can occur at room temperature with low threshold currents. It took many years for the material science of heterostructure fabrication to catch up with Kroemer's concept but now it is the industry standard. It was later discovered that the band gap could be controlled by taking the advantage of the quantum size effects in quantum well heterostructures. Quantum dot heterostructure laser is a type of laser diode. Laser diodes are used in laser pointers, barcode readers, DVD reading and writing, scanning, laser printing and optical communications.

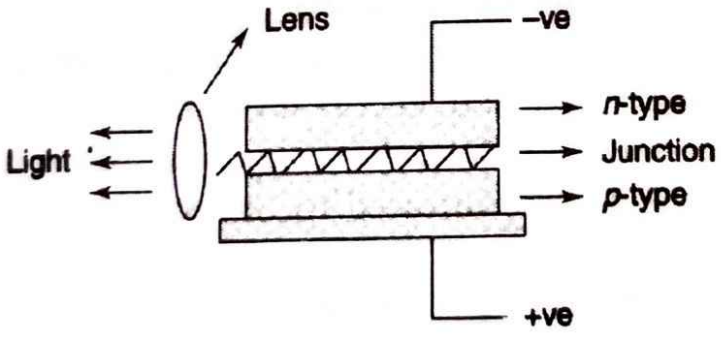


Fig. 6.1(a) : Schematic diagram of a quantum dot heterostructure laser diode

The schemating diagram of a quantum dot heterostructure laser diode is shown in the figure-6.1(a). It is constructed in form of p-i-n architecture where intrinsic i-region constitutes the active region of the laser diode. The charge carriers are pumped into the intrinsic i-region from both the n-region and p-region correspondingly. The photons are usually emitted at the bandgap energy or between the impurity levels and valence band. The light emitting region of a laser diode is very small of the order of few micrometers. The radiation spreads out rapidly from the laser diode due to the diffraction phenomenon taking place in the light emittiong regions. The emitted laser beams can be collimated by using suitable lenses. There are two basic approaches followed for the delivery of optical signals from laser diodes. One technique is fibre optic delivery and

other technique is free space delivery. In fibre optic delivery the output of the laser diode is channelled through an optical fibre. In free space delivery the output of the laser diode is directly focused and used. Laser diodes are ideal sources of photons for applications in tele-communications, signal processing, medical diagnostics and material characterization.

6.2 OPTICAL SWITCHING

In recent years semiconducting nanomaterials are intensively used in both academic and industrial research because of their electronic and optical properties for the constructionof advanced optoelectronic nanodevices. The fabrication of nanostructured materials with controlled structures and novel properties is very important for such applications. The opto-electronic response and surface chemical properties of nanomaterials were found to be promising for the successful demonstration of optical switches and detectors. Presently most of the communication and networking equipments are based on electrical signals. Hence the optical signals must be converted into electrical signals and amplified, regenerated or switched. Then the electrical signals are reconverted to optical signals for transmission. This process is commonly known as optical-to-electrical-optical (OEO) conversion. Hence the basic requirement of optical switching is to replace the existing electronic network switches by the optical switches to eliminate the need for OEO conversion.

The advanges of avoiding OEO conversion, are :

(i) Overcome the complexity in OEO conversion.

(ii) Optical switching is cheaper.

(iii) Physically smaller switches can be fabricated.

Recently optical swtiches are considered as the key features in fibre optic communication networks. Optical switching has become an important component in tele-communication sector. Currently optical switches are used in optical circuits, to select wavelength, restore the optical paths in case of link failure and for signal monitoring. Most of the optical switches are referred as optoelectronic devices because they convert optical input signal into an electronic signal for switching purposes. Then the electronic signals are used to drive the optical transmitter. Some optical switches can separate a particular wavelength readily. Optical switches can evaluate the signals in the form of light radiation which could be either in the form of a fined wavelength or multiple wavelengths.

There are a number of techniques developed for the fabrication of optical switches. Some techniques are briefly explained below.

Opto-mechanical switches : Optical switching was commercially visualized through opto-mechanical technology. The switching functions are done by mechanical means with the help of prisms, mirrors and directional couplers. The electro-mechanical actuators are also used in these switches to redirect the light beam.

Electro-optic switches : If an electric fild is applied this device then starts to vary non-isotropically as a function of refractive index of the target in the device. The variation in refractive

index guides the light through the appropriate path to the desired port. The switching functions are extremely fast and reliable in electro-optic switches but the insertion loss ruin the overall efficiency.

Thermo-optic switches : These devices are based on thermo-optic effect. The temperature variation in the material causes variation in its refractive index. This helps in guiding the light. In these devices driving voltage performs switching actions.

Electro-holographic switches : In these devices the switching functions are controlled by means of an electric field and hologram. These switches are based on beam deflection method.

Bubble siwthces : These devices are made up of two layers of silicon where one serves as the optical signal transmitter and the other is linked with inkjet technology.

Liquid-crystal switches : These devices are based of polarisation of light. If a desired voltage is applied across the crysal layer then the light is switched between two states. The light passes through in one state but does not pass through in other state.

6.3 OPTICAL DATA STORAGE

Optical data storage is the storage of data on optically readable medium. Data is recorded by making marks in a pattern that can be read back with the help of a beam of laser light focused on a spinning optical disc. Microform is an older example of optical data strorage that does not require the use of computer. There are different methods of optically storing data. An optical disc drive is a device in a computer that can read CD-ROMs or other optical discs such as DVDs and blu-ray discs. Optical data storage differs from other storage device such as magnetic data storage. Optical data storage can range from a single drive reading a single CD-ROM to multiple drives reading multiple discs such as an optical juke box.

Single compact disc (CD) can store around 700 MB data and optical juke box can store much more data. Single-layer DVD can store 4.7 GB data but dual layer DVD can store 8.5 GB data. Double sided DVD with readable surfaces on both the sides of the disc can store from 9.4 GB to 17 GB data. High definition (HD) DVD can store 15 GB data with a single layer and 30 GB data with a dual layer. Blu-ray disc can store 25 GB data with a single layer and 50 GB data with a dual layer.

Nanomaterials can be used for the development of disruptive methods for optical data storage with ultra high capacity, ultra long lifetime and ultra low energy consumption because they have unique, mechanical, electronic and optical properties causing the strong confinement of electrons, photons and phonons at the nanoscale.

6.3.1 OPTICAL MEMORY

Optical memory is the latest mass memory technology which has a promising future. The operation of an optical memory is based on the reflection or scattering of an extremely narrow laser beam off a disk that has microscopic pits or bubbles representing logic is burned on its suface. Optical memories are of three types namely compact disk, digital versatile disk and blue ray disk.

Compact Disk (CD) : CD is an optical storage device having a storage capacity of upto 700 MB. It is relatively cheap. There are three types of CDs namely CD-ROM, CD-R and CD-RW.

CD-ROM : CD-ROM devices are mass produced in factory using a stamp press technology. CD-ROM drives use LASER technology to read data from it. A semiconductor LASER generates a high intensity light wave of stable wavelength $\simeq$ 780 mm. A lens system directs the LASER towards the disk over 1 μm diameter spot. The intensity of the reflected light from metallic reflection layer received by photo sensors gives the information of binary data stored in the CD. There are two different surfaces called pit and land from which reflection occurs. The pit is 0.12 μm deep compared to land and reflected intensities are about 25% and 70% from the pit and land respectively. The intensity of reflected light changes every time laser beam travels from land to pit or pit to land. This change is read as binary 1 and a constant intensity reflected light is interpreted as zero. The pit width is such that there is at least 2 and at most 10 zeroes between every binary 1. This is done by converting every 8-bit byte into a 14-bit value by a process known as eight to fourteen modulation (EFM). The diameter of a CD-ROM is 12 cm and its depth is 1.2 mm. The depth of a CD-ROM has four parts namely label layer, protective layer, reflective layer and transparent substrate layer. The pits and lands are formed on the transparent substrate layer. The CD-ROM is highly reliable because the data is protected by 10-20 μm thick protective lacquer layer on one side and label on the other side of 1.2 mm thick polycarbonate layer. Hence the data can be maintained for years without any loss in normal physical abuses. The small scratches on the surface do not directly erase the data but create extra areas of light scattering. The data is stored in the form of a spiral of around 20000 windings totaling 4.5 km of length and it contains 2 billion shallow pits on the surface. The symbol on the CD-ROM represents the speed at which data is read from the CD-ROM. The symbol 1X stands for 150 Kbps. CD-ROMs are available today in speed range of 48X to 75X.

Example - 1 : What is the speed of a 48X CD-ROM ?

Ans. 48X = 48 × 150 Kbps = 7200 Kbps.

Example - 2 : What is the speed of a 75X CD ?

Ans. 75X = 75 × 150 Kbps = 11250 Kbps.

CD-R : Compact Disk - Recordable allows to write data only once and it can not be erased. The CD-R drive has LASER unit that uses higher intensity light wave for write operation than that for read operation. CD-R disk does not have pits and lands but it has a photo-sensitive organic dye between reflective layer and polycarbonate substrate that write laser heats to nearly 250°C. This melts the dye to form a depression mark in the recording layer in proper places. The places burnt have lower reflectivity of light. Hence read laser has two different intensities on reflected light while reading the disk. Earlier version of CD-R was called as WORM i.e., write once read many times. WORM requires data to be written in only one session or one go. Now CD-R can be written in multiple sessions till it is completely filled. The writing speed of CD-R is much slower than the read speed.

CD-RW : Compact Disk - Rewritable or CD read write is an erasable disk in which data can be written and erased many times. CD-RW uses an active layer of silver-indium-antimony-tellurium alloy that has a polycrystalline structure making it reflective. Writing data on CD-RW uses highest power of laser which heats the selected places to 500°–700°C. At this high temperature the chemical structure liquifies loging its polycrystalline structure and cooling solidifies to an amorphous state whose reflectivity is reduced from 25% to 15%. The read operation on CD-RW is like CD-ROM and CD-R that notes the difference in reflectivity on the reflecting surfaces. To erase data the LASER operates at a lower power setting and heats the active material to 200°C. This converts the material from amorphous state to its polycrystalline structure and makes the material reflective again. In a CD-RW the rewrite operations can be done 1000 times or more. 12X/10X/32X/ CD-RW indicates that CPU and media permitting CD-drive can write to CR-R disk at 12X speed, write to CD-RW disk at 10X speed and read from CD at 32X speed.

DVD (Digital Versatile Disk) : DVD is also known as Digital Video Disk and it is an optical storage device that looks like a compact disk. DVD is able to store nearly 15 times data more than that store by CD. It can transfer data to the computer about 20 times faster than CD-ROM. DVD is also known as Super Density Disk (SD) and can store data upto 17 digabytes. It can also store four hours of movies on one side. DVD drives use smaller wavelength (635 mm or 650 mm) and lower numerical aperature lens system to read smaller dimension land and pits. Each side has two layers from which data is read and in certain disks data is written on both the sides of DVD. Single sided single layer DVD has a storage capacity of 4.7 GB, single sided double layer DVD has a storage capacity of 8.5 GB, double sided single layer DVD has a storage capacity of 9.4 GB but double layer DVD has a storage capacity of 17.1 GB. In DVD terminology 1X means 1.32 Mbps. There are three types of DVDs namely DVD-ROM, DVD-R and DVD-RW.

DVD-ROM : Digital Video Disk - Read only memory is an optical storage device having storage capacity between 4.7 GB to 17.1 GB. DVD-ROMs were originally developed for the movie industry. Huge capacity makes them attractive for storing large amounts of data. DVD-ROM drives can read audio CDs, CD-ROMs, CD-Rs and CD-RWs.

DVD-R : Digital Video Disk - Recordable allows to write data on the disk only once and read it many times but the data can not be erased.

DVD-RW : Digital Video Disk - Rewritable or DVD-read write is an erasable disk in which data can be written and erased many times.

Blue-ray Disk (BD) : BD is an optical storage disk format which has the same dimensions of a standard DVD or CD. BD is mainly used for high definitions (HD) video and data storage. The BD format uses a blue-violet laser instead of red laser. The new BD formt can store five times more data than DVD can store. The storage capacity of BD is upto 25 GB on a single layer disk and 50 GB on a double layer disk. BD is used for recording rewriting, playback of HD video and storing large amounts of data. The advantages of using blue-violet laser of wavelength

405 nm is that it has a shorter wavelength than red laser of wavelength 650 nm which makes it possible to focus the blue-vioet laser with even greater percision. This allows the data to be packed more tightly and stored in less space. Therefore it is possible to fit more and more data on the blue ray disk.

6.4 MAGNETIC QUANTUM WELL

Magnetic quantum well is a potential well with only dicrete energy values.

Magnetic quantum well is formed in magnetic semiconductors sandwiched between two layers of a material with a wider bandgap.

Magnetic semiconductors are the semiconductors which exhibit the property of ferromagnesium. These semiconductors would allow control of quantum spin state if implemented in devices. Dilute magnetic semiconductors (DMS) are semiconductors doped with transition metals. These magnetic semiconductor are used in spintronics. Spintronics is the study of intrinsic spin of electron and its magnetic moment in addition to electronic charge in solid state devices.

Magnetic quantum well can be grown by molecular beam epitaxy or chemical vapour deposition with control of the layer of thickness down to monolayers.

Thin metal films can also support quantum well states, in particular, metallic thin layer are grown in metal and magnetic semiconductor surfaces. The electron or hole is confined by the vacuum-metal interface in one side and by an absolute gap with semiconductor substances or by a projected band gap with metal substrates.

Magnetic quantum wells are used for the fabrication of spin transistors and spin polarised LEDs.

6.5 MAGNETIC QUANTUM DOTS

Magnetic quantum dots are very small magnetic semiconductor particles having several nanometres in size. They are so small that their optical and electronic properties differ from those of larger particles. They emit light of specific frequencies if electricity or light is applied to them. They tightly confine electrons or holes. Magnetic quantum dot is a single object with bound or discrete states as in the case of atoms. Hence Magnetic quantum dots referred to as artificial atoms. They show the properties which are intermediate between those of bulk semiconductors and those of discrete molecules. Their optoelectronic properties change with the change of shape and size. Larger magnetic quantum dots (5 - 6 nm) emit light of longer wavelengths resulting in emission of colours such as orange or red. Smaller Magnetic quantum dots (2 - 3nm) emit light of shorter wavelengths reslting in emission of colours such as blue and green. Magnetic quantum dots are used in transistors, solar cell, LEDs, diode lasers, quantum computing, medical managing, inkjet printing and spin coating.

6.6 MAGNETIC DATA STORAGE

Magnetic data storage is the storage of data on a magnetized material. Magnetic storage is

also known as magnetic recording. It uses different patterns of magnetisation in a magnetic material to store data. It is a form of non-volatile memory. The information is accessed by using one or more read/write heads.

Hard disks are the magnetic storage devices which are widely used to store computer data as well as audio and video signsals. The term magnetic storage is preferred in the field of computing and the term magnetic recording in preferred in the field of audio and video production. Other magnetic storage devices are floppy disks, magnetic tape and magnetic stripes on debit/ credit cards.

Early magnetic storage devices were used to record analog audio signals. Now computers and most audio and video magnetic storage devices record digital data. In old computers magnetic storage was used for primary storage in a form of magnetic drum or core memory, thin film memory twister memory, bubble memory. In modern computers mangnetic tape is also used for secondary storage.

Information is written to and read from the storage medium as it moves past read and write heads that operate very close over the magnetic surface. The read and write head is used to detect and modify the magnetisation of the material under it. There are two magnetic polarities each of which is used to represent 0 or 1.

In older hard disk drive the magnetic regions were oriented horizontally and parallel to the disk surface but in modern hard disk drive the magnetic regions were oriented vertically and perpendicular to the disk surface. Older hard disk drive uses ferrous oxide as the magnetic material but modern disks use a cobald-based alloys. Magnetic nanostructures are being developed for data storage with high capacity because they have unique mechanical, electronic and magnetic properties causing strong confinement of electrons, photons, and phonons at the nanoscale.

6.6.1 MAGNETIC MEMORY

Magnetic memory includes the recording of digital information on mangetic tape, hard disk and floppy disks. Magnetic storage devices are quite sophisticated and are externally accessed. Magnetic memories are capable of storing large quantities of digital data. Magnetic disks (hard disks and floppy disks) are referred to as the mass memory because they can store huge amounts of data. Magnetic disks are important components in almost all micro-computers and mini-computers. Large reels of magnetic tape are economical and widely used in mass storage components in large computer system. The basic principle used in each case is the magnetization of small spots in the thin film of magnetic material. The principle of writing (recording or storing) binary data on a magnetic surface is shown in the figure. The write head is a small electro-magnet placed very closed to a moving magnetic surface.

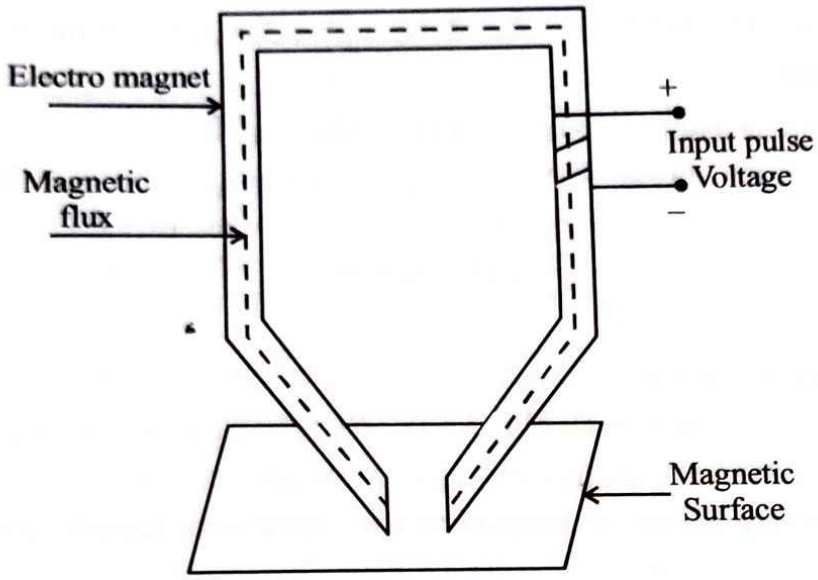


Fig : Magnetic Recording

When input pulse voltage is applied to the coil of the electromagnet the region of the magnetic surface under the electromagnet is magnetized in a certain direction. When a voltage pulse of opposite polarity is applied the region under the electromagnet is magnetized in the opposite direction. A data bit 1 or 0 is thus imprinted on the region disregarding the existing state of magnetization of the region. The principle of reading binary data from a magnetic surface is shown in the figure. The read head is a small electromagnet placed very close to a moving magnetic surface.

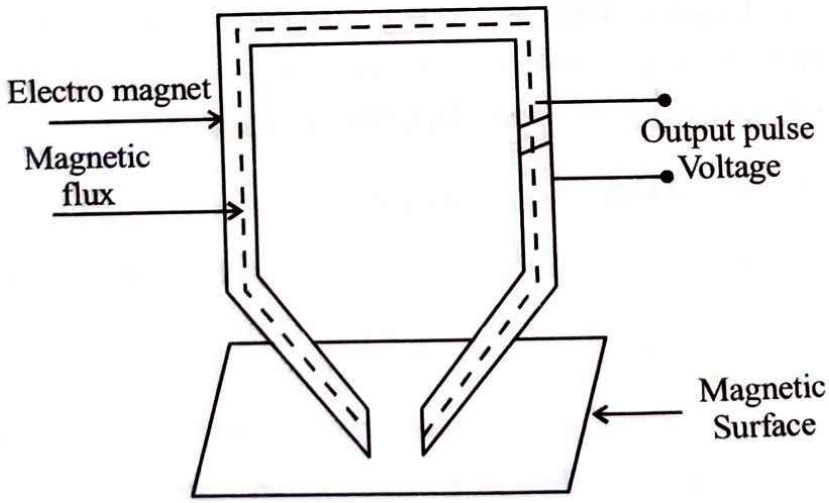


Fig - 8.12 - Magnetic Reading

The magnetized region (recording 1 or 0) under the electromagnet induces a voltage pulse of a certain polarity in the coil depending on the direction of magnetization of the region and indicates wheather the recorded bit is a 1 or 0. In most cases the read head and the write head are combined to form a single unit which is known as dual read-write head.

Magnetic Tape : Magnetic tape storage is non-volatile. It has immense capacity of storing data at relatively low cost per bit. It is a mass storage and back up device. A single magnetic tape may be of very long length and can store thousands of megabyte. The magnetic tape is wound on reels and must be unwound to read and write. The main drawback of the magnetic tape is the long time required to access a specific block of data. The magnetic tape is produced by the deposition of a thin film of magnetic material on a long strip of plastic which is then would on a reel. The adjacent regions on the surface of the magnetic tape are magnetized with one polarity on the other to represent 1 and 0 and dual read-write head is used to sense or alter the magnetization. Data can be recorded on magnetic tape either in coded form or in binary form. Either seven or nine dual read-write heads are connected in parallel for use with magnetic tape. As the magnetic tape moves past the heads, data is read or written. In the 7-bit system, alpha-numeric information is recorded in the coded form and there is 1 parity bit. In the 9-bit system a data is composed of 8-bits and the ninth bit is for parity either even or odd. Data storage on a magnetic tape is sequential.

Hard Disk : Hard disk is produced by the deposition of magnetic material on a thin circular rigid disk (usually aluminium). It is a secondary storage device and is used for both sequential and random access. The recorded data can be read many times without disturbing the recorded information. The recorded data can be erased and new data can be recorded. Hence the hard disks are known as read-write devices. They can store several gigabyte of data. The hard disk is sealed along with its drive mechanism in a dust-free environment. In a hard disk small magnetised patches are created on the magnetic coating to record data. The magnetization in a certain direction of a patches represents a 0 but the magnetization in the opposite direction of a patch represents a 1. The binary bits are recroded on concentric circles called tracks. These tracks are divided into sectors as shown in the figure.

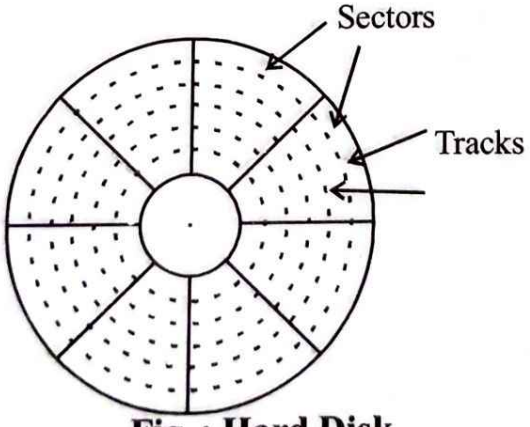


Fig : Hard Disk

The hard disks used in small computer system are 3.5 inches or 5.25 inches in diameter. Hard disks drive with 40 to 400 gigabyte capacities are common in micro-computer systems. Hard disk is rotated at speed between 3600 to 7200 rpm. In high end computer hard disk rotates at speed 1500 rpm resulting an access time of 16 ms to 36 ms. Hard disks are widely

used in computer system because of short access time and high storage capacity. The number of tracks and sectors are different for different computer systems and for different manufacturers. The smaller hard disks used in micro-computer systems have around 300 tracks. In a modern computer system there are options to use 3.5 inch hard drives of capacity 80 GB and above, 2.5 inch hard drive of capacity 40 GB to 120 GB and palm size pocket hard drive of capacity 2.5 GB and 5 GB in addition to internal hard disks.

Floppy Disks : Floppy disk is produced by the deposition of magnetic material on a semirigid plastic disk. Floppy disks are also known as diskettes or floppies. The floppy disk is permanently housed in a flexible square jacket that protects the disk from dust.

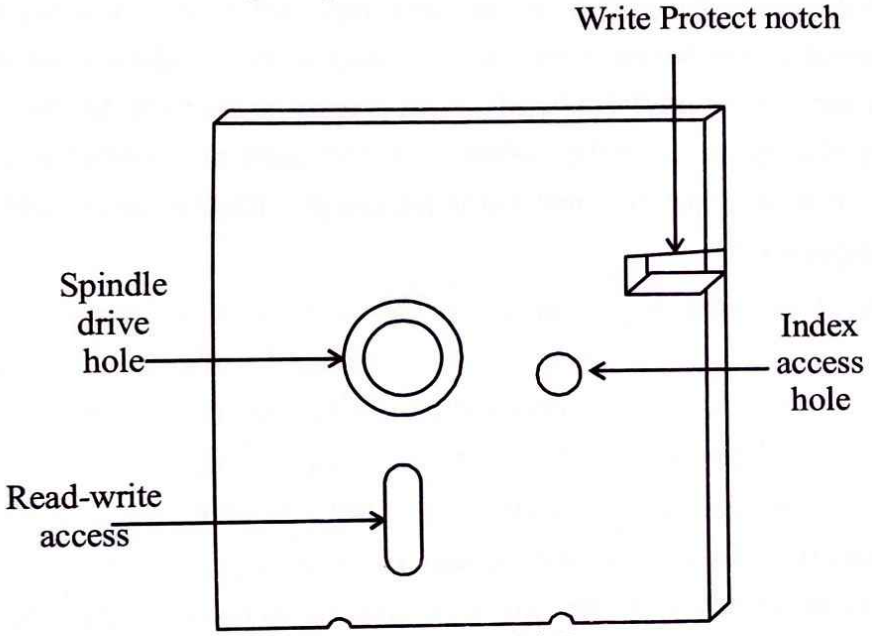


Fig : Floppy Disk

The read-write opening provides access for the read write head. The index access hole allows the use of photo-sensor to establish a reference position. When the write protect notch is covered, data can not be recorded on the disk and loss of data is prevented. The floppy disk is a portable storage device and it must be inserted into a disk drive. The disk drive unit consists of a single read-write head, a write mechanism and a track positioning mechanism. The spindle drive rotates the magnetic disk at a speed of 360 rpm. Hence the access time for floppy disk is about 80 ms. It is a random access device. It is also divided into tracks and sectors depending upon the data to be recorded. Double sided high density 5.25 inch floppy disk has a capacity of 1.2 MB. Double sided high density 3.5 inch floppy disk has a capacity of 2.88 MB.

Example - 1 : A single-sided double density 8-inch floppy disk has tracks numbered 0 to 76 and sectors 0 to 25. What is the total storage capacity of the disk ?

Ans. Number of sectors = 26

Number of tracks = 77

Bytes per sector = 256

$\therefore$ Storage capacity of the disk = $77 \times 26 \times 256 = 512.512$ bytes.

Example - 2 : The total storage capacity of a floppy disk having 80 tracks and storing 128 bytes/sector is 163840 bytes. What is the number of sectors of the disk ?

Ans. Number of sectors $= \frac{163840}{80 \times 128} = 16$.

6.7. MICRO ELECTRO-MECHANICAL SYSTEMS

Micro Electro-mechanical systems are a special class of semiconductor devices that employ mechanical functions with integrated circuits. MEMS technology involves the study on micro-mechanical components and systems which are integrated with electronics on a package to achieve high performance functional systems. MEMS are also referred to as micro-machines or micro-systems technology. MEMS are made up of components between 1 and 100 micro-metres in size and MEMS devices generally range from 20 micro-metres to 01 millimetre, although components arranged in arrays can be more than 1000 mm^2. MEMS devices usually consist of a central unit that processes data and several components that interact with the surroundings.

The fabrication of MEMS are based on deposition of material layers, patterning by photo-lithography and etching.

MEMS devices can be made from silicon. Silicon is the material used to create many integrated circuits used in consumer electronics in the modern industry. It is attractive for a wide variety of MEMS applications due to its low cost, high quality and readily availability. It is an almost Hookean material because when it is flexed there is virtually no hysteresis and almost no energy dissipation. It is reliable for highly repeatable motion because it suffers a little fatigue. It can have service lifetimes in the range of billions to trillions of cycles without breaking.

MEMS devices can also be made from polymers. Polymers can be produced in huge volumes with a great variety of material characteristics. MEMS devices made from polymers are well suited to microfluidic applications like disposable blood testing catridges.

Metals can also be used to create MEMS device . Metals can exhibit very high degree of reliability although they do not have some of the advantage. shown by silicon in terms of mechanical properties when used within their limitations. Metals can be deposited by electroplating, evaporation and sputtering processes. Gold, nickel, aluminium, copper, chromium, titanium, tungsten, platinum and silver are used to create MEMS devices.

In MEMS fabrication the nitrides of silicon, aluminium and titanium, silicon carbide and other ceramcs are used due to the advantages of materials. Aluminium nitride shows pyroelectric ad piezoelectric properties. Titanium nitride exhibits a high electrical conductivity and large elastic modulus. These are used in sensors. MEMS basic processes are deposition processes, patterning, lithography and etching. MEMS devices contain mechanically movable parts that are used for sensing and control applications. MEMS played a pivotal role in transportation, communication, automated manufacturing, environmental monitoring, health care, deference systems and other

wide range of consumer applications. MEMS structures can be used for the fabrication of electronic components, micro-engines and micro-mirrors, capacitors, inductors and switches. The developments in micro-fabrication technologies have enabled the miniaturization of electro-mechanical devices and their batch processing significantly. MEMS based optical systems have also been used as real heads in disk drives, laser prints, bar code readers and scanning machines.

Some common connercial applications of MEMS are :

(i) Inkjet printers use piezoelectrics or thermal bubble ejection to deposit ink on paper.

(ii) Accelerometers are used in cars for a large number of purposes including airbag deployment and electronic stability control.

(iii) MEMS accelerometers and MEMS gyroscopes are used in remote controlled helicoptors, planes, drones for automatically sensing and balancing flying characteristics of roll, pitch and yaw.

(iv) MEMS magnetic field sensor is used in remote controlling drones to provide directional heading.

(v) MEMS are used in inertial navigation systems of modern cars, air-planes, submarines and other vehicles to detect yaw, pitch and roll like autopilot of an airplane.

(vi) MEMS accelerometers are used in consumer electronic devices such as game controllers, personal media players, cell phones, digital cameras ad personal computers.

(vii) MEMS microphones are used in portable devices such as mobile phones, head sets and laptops.

(viii) MEMS silicon pressure sensors such as car tire pressure sensors and disposable blood pressure sensors are used in respective fields.

(ix) MEMS displays such as digital micromirror device chips are used in display system.

(x) Optical switching technology which is used for switching technology and allignment for data communications.

(xi) Bio-MEMS are used in medical and health related technologies (biosensor, chemosensor).

(xii) Micro-machined ultrasound transduces such as radar and sonar are used in various fields.

(xiii) Micro-scale energy harvesting including piezoelectric, electrostatic and electromagnetic micro harvesters are the application of MEMS for energy harvesting.

(xiv) Non-invasive surgical tools, cardiology related micro-systms, drug delivery systems, biomedical analysis, patient monitoring systems, artificial organs, hydrocephalic shunts, artificial lenses, digital implants, pacemaker, artificial heart components, skin electrode for ECG, artificial joints are the biomedical applications.

6.8 NANO ELECTROMECHANICAL SYSTEMS

Nano-electromechanical systems are a class of devices integrating electrical and mechanical

functionality on the nanoscale. NEMS typically integrate transistors like nano-electronics with mechanical pumps, mechanical actuators and motors and form physical, biological and chemical sensors. AFM tips are the key applications of NEMS.

The fabrication of NEMS are based on top-down approach, optical electron beam lithography and thermal treatments.

NEMS technology is based on the use of the allotropes of carbon, such as diamond, carbon nanotube and graphene. The mechanical properties of carbon allotropes are the fundmental to the stability of NEMS and the metallic and semiconductor condutivities of carbon allotropes allow them to function as transistors. Graphene and diamond have high Young's modulus, low density, low friction and large surface area. Carbon nanotubes have low friction which allows practically frictionless bearings. CNTs are used as the elements of NEMS such as nanomotors, switches and high frequency oscillators. The physical strength of CNTs and graphene allow them to meet higher stress demands. The electrical properties of carbon nanotubes and graphene allow them to be used in many electrical components of NEMS. Nano-transistors have been developed from carbon nanotubes and graphene. Metallic carbon nanotubes have also been proposed for nano-electronic interconnects since they can carry high current densities.

The applications of NEMS are :

(i) Nano-electromechanical relay is an electrically actuated switch that is built on the nano scale using semiconductor fabrication techniques.

(ii) Nano-electromechanical systems mass spectrometer is an instrument used for measuring the mass of analyte particles by detecting the frequency shift caused by the adsorption of the particles on an NEMS resonator.

The advantages of NEMS technology are :

(i) Miniaturization and easy to integrate.

(ii) Low-cost fabrication using batch process.

(iii) Highly adoptable for large scale fabrication.

(iv) Easy to access

NEMs technology has received huge expectations to integrate engineering devices with life sciences. However, this is highly impossible with the currently available microscale technologies. For example, in case of drug delivery applications it is highly required to maintain a certain degree of concentration for the drug so that thay can react accordingly to procure the desired therapeutic effect. In this case any upper or lower limit in the concentration would seriously affect the potential of such therapies. Hence to overcome such hardships micro-dosing is being engineered using micropumps, micro-sensors and microfluid channels with other essential circuits.